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LaRC Computational STRUCTURAL DYNAMICS OVERVIEW

PRESENTED AT

CSM 1987 WORKSHOP

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LaRC Computational Structural Dynamics Overview

OBJECTIVES

Develop Advanced Computational Methods For Transient And Simulation Analyses of Aircraft, Launch Vehicles and Space Structure Components

ACTIVITIES:

In-House

- Development of Multibody Simulation Tool
- Procedures for Articulating Structures

Out-of-House

- Subcycling in Parallel Computing Environment
- Large Deformation/Motion Beam Formulation
- Constraint Stabilization
- Direct Integration Transient Algorithms in Parallel Computing Environment

LANGLEY RESEARCH CENTER COMPUTATIONAL STRUCTURAL DYNAMICS OVERVIEW

Present research centers on the development of advanced computational methods for transient simulation analyses. Aircraft, launch vehicles and space structure components are potential applications, but primary focus is presently on large space structures.

There are both in-house and out-of-house activities. The in-house activity centers around the development of a multibody simulation tool for truss-like structures called LATDYN for Large Angle Transient DYNamics. Multibody analysis involves articulation of structural components as well as robotic maneuvers. These items are necessary for construction (erection or deployment) of large space structures in orbit and the carrying out of certain operations on board the space station. Thus part of the in-house activity involves the development of methods which treat the changing mass, stiffness and constraints associated with articulating systems.

The out-of-house activity involves subcycling, development of large deformation/motion beam formulation, constraint stabilization and direct time integration transient algorithms in parallel computing.

RECENT PROGRESS - Out-of-House Research

- Subcycling Explored With Vectorization and Concurrency
  - Preliminary Tests Indicate Speed Increases on the Order of 10 +
- Multi-body Dynamics Developments
  - Hierachical Flexible Beam Elements
  - Staggered Constraint Stabilization Procedure
  - Integration of Large Rotation Equations
  - Automated Partitioning Procedure
- A Non-Conventional Partitioning Procedure Developed
  - PANTA (Partitioned Algorithm for Nonlinear Transient Analysis)
  - Speed Increases Due To Both Partitioning and Concurrency

RECENT PROGRESS - Out-of-House Research

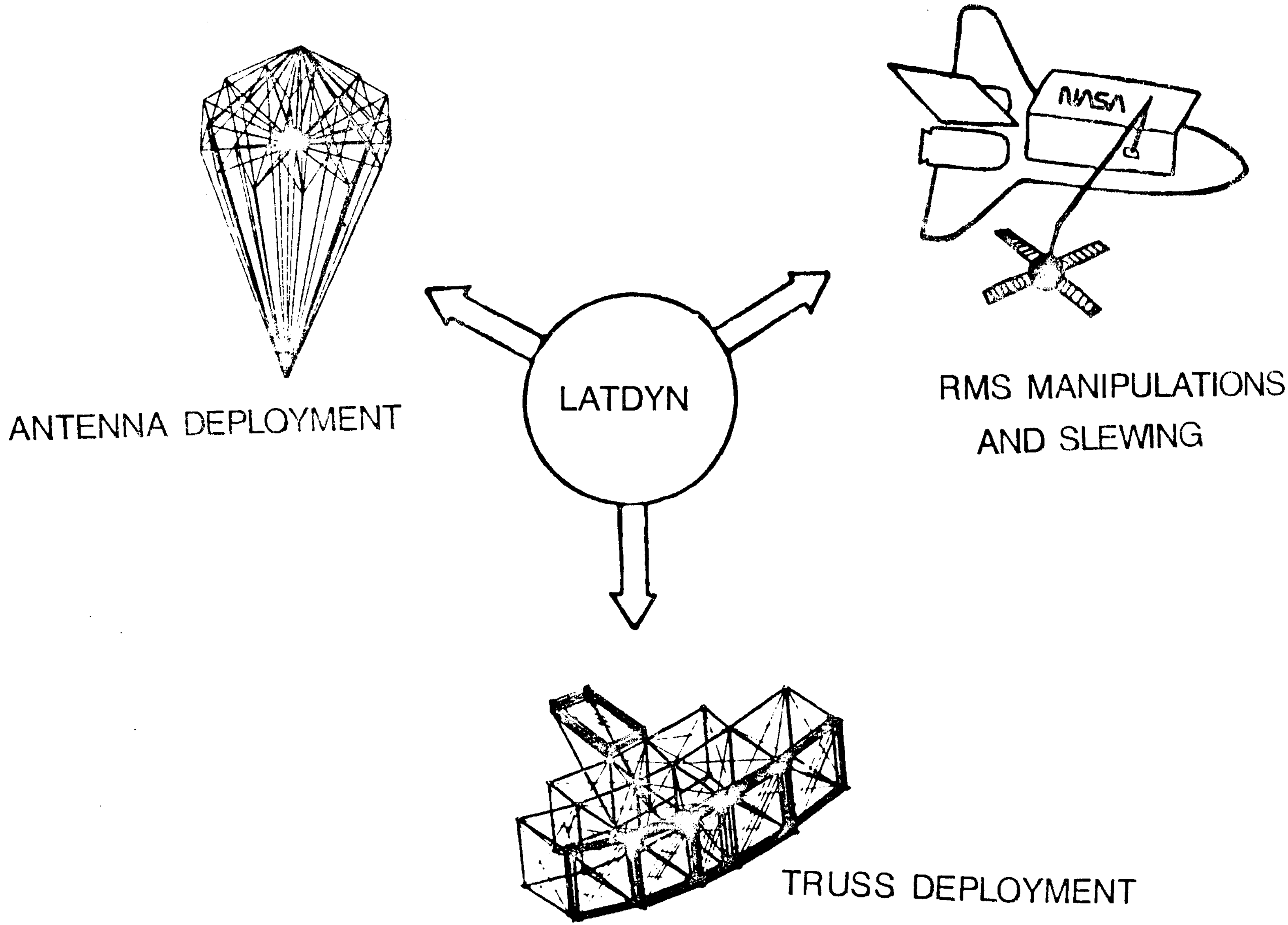
Subcycling or spatially non-uniform time step procedures for explicit temporal integration has particular emphasis on the trade-off between long vectors for vectorization efficiency and blocking of operations for use of many computational processors in parallel. This work is being accomplished at Northwestern University. Preliminary trade-off studies involving vectorization and concurrent processing indicate speed increases on the order of 10+ are possible.

At the University of Colorado, a large deformation/motion beam formulation has been developed which treats translational and rotational motions in two separate ways and allows for transverse shearing members or components. The university has also developed a constraint stabilization technique which uses a penalty function approach and has exhibited much potential on sample problems.

Finally, a direct integration transient algorithm has been established for use in a parallel computing environment. The method exhibits considerable efficiency even on a sequential machine and in a parallel environment the method appears to be a significant breakthrough.

LATDYN

Large Angle Transient DYNamics



LATDYN

The LATDYN (Large Angle Transient DYNamics) computer program is an analytical simulation tool for multi-body structural dynamics behavior involving large angle rotation between structural components. The tool finds application in large space structure deployment, robotic arm manipulation and modeling of deformable mechanisms. It has been developed at the Langley Research Center through a team effort composed of NASA and contractor (the COMTEK Company) personnel. The program has not been developed as a commercial production code, but rather as a research code which provides a testbed for studying computational aspects of this class of problems. Presently, only a two-dimensional working version exists. The program is written in FORTRAN 77 and is operational on the VAX/VMS and CDC/NOS. Extensive graphics output capability is provided including line drawings, and deformed and undeformed geometry. A three dimensional version is under development.

LATDYN CAPABILITIES

Finite Element Based

- General geometry including closed loop topologies

Rigid or Flexible Beams

Applied Forces,Displacements,Velocities or Accelerations

Fortran Based Command Language

- Permits external user access to internal fortran code
- User written logic commands provide added control over program flow

Nonlinear Springs and Dampers

Control Forces

- Functions of system variables
- Time delay

Lock-up, Docking, Impact

LATDYN CAPABILITIES

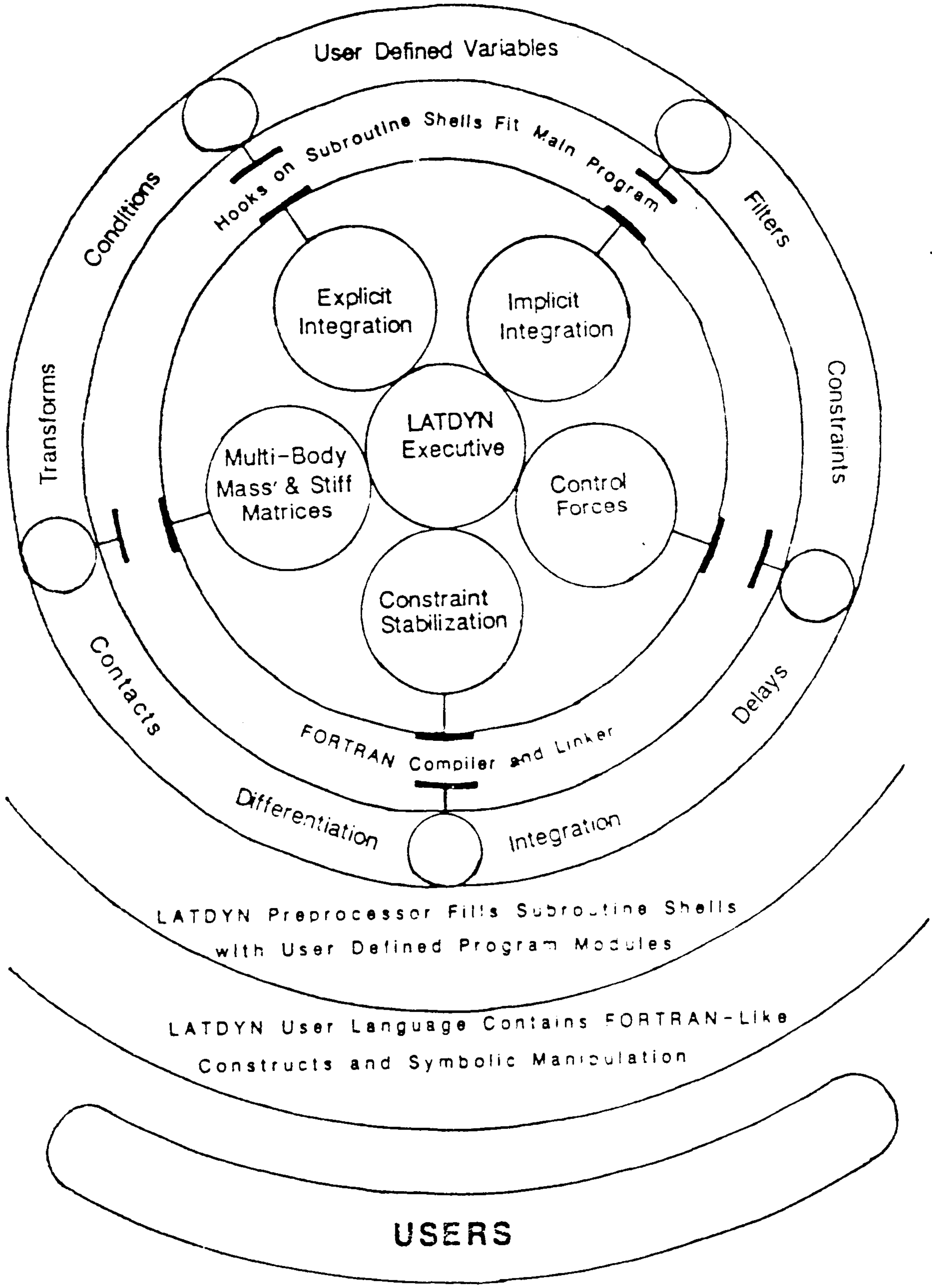
LATDYN is a finite element structural program. It is intended for use in classes of problems where the multi-body system undergoes some deformation; that is, there is some strain energy associated with the motion. The structure is modeled with a mesh of finite elements as in any finite element program. The program does not depend upon mode shapes to characterize motion of the component bodies, rather , component bodies are discretized into finite elements. As in most finite element codes, generalized coordinates map the motion of the element end points and shape interpolation functions characterize motion internal to the element. However, provision is made for global shapes on the component level. One significant advantage of a finite element approach is its allowance for general geometry, including closed loop topologies, as attested to by its wide popularity in the structures community.

Presently, the library of elements is limited to rigid or flexible beams, springs, dampers and lumped masses. Use of a convected coordinate system, described on a subsequent chart, permits the beam members to undergo unlimited rotations and large deformations. The user may specify either applied forces, displacements, velocities or accelerations.

A FORTRAN based language allows the input of user defined relationships thereby permitting the definition of nonlinear springs, dampers, control forces which are functions of system variables, time delay and a host of other capabilities. Furthermore, user written true or false logic commands make use of all FORTRAN logic statements, (such as, .AND., .OR., IF, etc.), to permit the user an added degree of control over which commands are executed and their order of execution.

In addition, time varying constraints are permitted, and an algorithm known as ACCIDS (Algorithm for Constraint Changes In Dynamic Systems), as discussed in reference 2 and on a subsequent chart, is used to perform lock-up, docking, impact or any other situation where system constraints change suddenly.

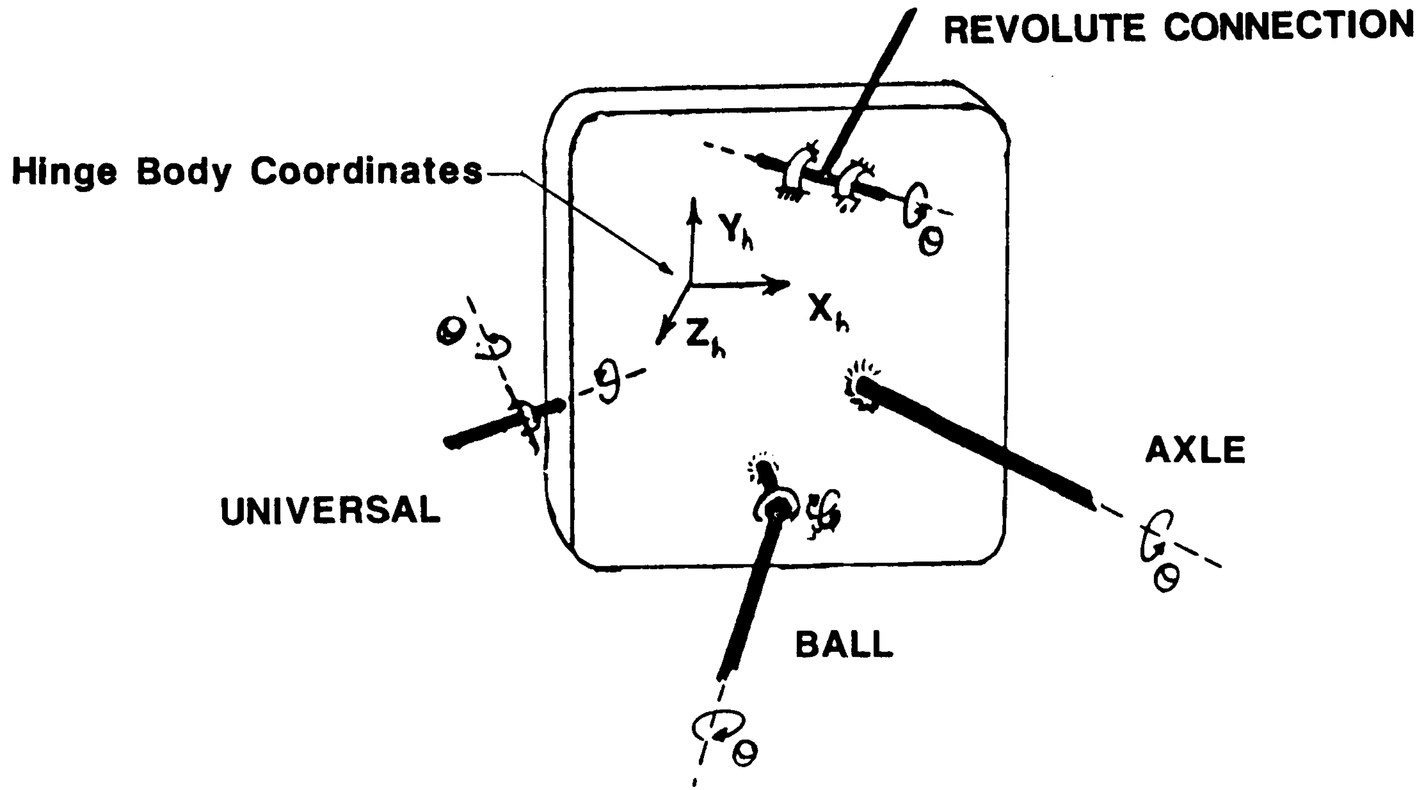
LATDYN FRAMEWORK



LATDYN FRAMEWORK

The figure schematically illustrates the framework of the LATDYN program. The user communicates with the program through a FORTRAN-like command language. A preprocessor interprets the commands and generates FORTRAN code which fills a shell of potential program capabilities. Hooks and scars on the core of the LATDYN program permit the shell to become part of the program via the computer system's FORTRAN compiler and linker. This provides the user easy access to the internal code without having to compose user written subroutines which invariably are very cumbersome for the average user.

GENERIC HINGE BODY WITH MEMBER CONNECTIONS



Define:

$[\Gamma]$, Fixed Orientation of Hinge Connection Relative to Hinge Body

θ, Time Varying Rotation About a Hinge Line

GENERIC HINGE BODY WITH MEMBER CONNECTIONS

The class of structures to be treated by this program are joint dominated. That is, the mass of the interconnecting joints between the bodies represents a significant portion of the total mass and the orientation of the joint's hinge lines plays an important role in determining structural behavior and whether or not a mechanism exists. It is thus reasonable to construct the finite element program with the joints, herein denoted as hinge bodies as a part of the element connectivity. This avoids numerical problems which can arise due to what might be called "the tail wagging the dog" phenomenon. Furthermore, since large angular rotations are not vectors, connectivity relationships could be time varying and quite complex. The use of hinge bodies circumvents these connectivity complications. Thus, the hinge bodies are introduced into the formulation from the outset.

A generic hinge body with several members connected to it through various types of joints is depicted in the figure. Accommodations for hinge connections to various members connected to the hinge body are built into the formulation. Again, this avoids the cumbersome and often difficult task of composing the time varying constraint relations to represent member connections. If there is no hinge, but rather a rigid connection, the constraint is set to zero. It is easier to set a constraint to zero than to create a complex time varying one.

A cartesian coordinate system is used to measure three translations of a designated point on a hinge body and a transformation matrix, T_h, provides the orientation of three orthogonal axes embedded into the hinge body. Members are assumed to be hinge-connected to a hinge body. The connecting hinge line is embedded into the hinge body and is related to the hinge body axes through a fixed transformation matrix Γ. The rotation, θ, about the hinge line is time varying.

Generalized Coordinates

For Each Hinge Body

- 3 Translational Displacements of Hinge Body
- 3 Angular Rotational Rates of Hinge Body
- 1 Relative Angle Between Hinge Body and Finite Element

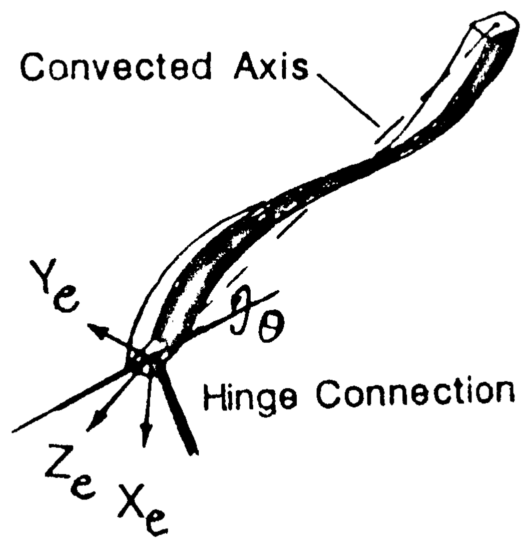
GENERALIZED COORDINATES

For each hinge body, there exist three translational generalized coordinates, three angular rotational generalized coordinates and one relative angle generalized coordinate for each hinge located on the hinge body.

DEFORMED FINITE ELEMENT

Element Coordinates Move

With Cross-Section



Deformations Are Measured From Convected Axes

Define:

$[\Gamma]$, Fixed Orientation of Hinge Connection on Finite Element

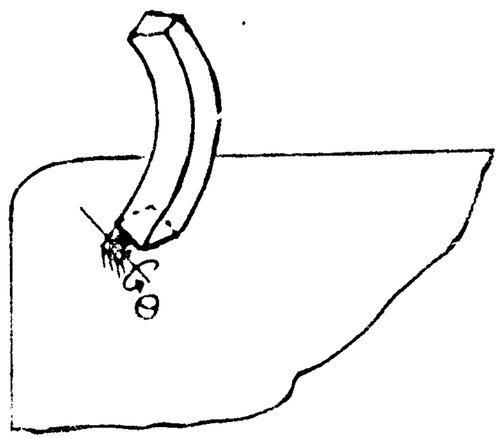
θ, Time Varying Rotation About Hinge Line

DEFORMED FINITE ELEMENT

Each structural member is divided into finite elements. A typical deformed element is shown in the figure. The orientation of the element at its ends is monitored by means of two element coordinate systems, one at each end, though only one is shown in the figure. These coordinates move with the element. The x-axis of the element system is tangent to the element at its end and the other two orthogonal axes are parallel to the principal axes of the element cross-section. The orientation along the length is found from an assumed polynomial shape function as in any finite element analysis. As with the hinge body, a hinge line is embedded into the end of the element with associated fixed transformation $\bar{\Gamma}$. The rotation, θ, about the hinge line is time varying.

A convected coordinate system is used to define a reference for measuring element flexural deformations. This separates rigid body and deformable motions. As shown in the figure, the convected x-axis connects the end points of the element. Its other two orthogonal axes roll with the element.

Connectivity of Finite Element/Hinge Body



Hinge lines on finite element and on hinge body coincide

On Hinge Body		On Finite Element
$T_h \, \Gamma \, \Gamma_\theta$	=	$T_e \, \overline{\Gamma}$

On Hinge Body:

- T_h: Transform to global system
- Γ: Transform to hinge body system
- Γ_θ: Rotate hinge connection

On Finite Element:

- $\overline{\Gamma}$: Orientation of embedded hinge line in finite element
- T_e: Transform to Global System

CONNECTIVITY OF FINITE ELEMENT/HINGE BODY

Since the hinge lines on the hinge body and on the finite element must coincide, and since axes orthogonal to the hinge lines must also coincide when rotated through an angle θ, the transformation from a global system to the element system, T_e, may be related to the transformation from the global system to the hinge body system, T_h,

$$T_e = T_h \Gamma \Gamma_\theta \Gamma^T$$

Thus in the analysis, T_h for the hinge body is monitored and θ for the hinge connection.

Element Deformations

Deformation matrix is product of transformation matrices

$$\text{Deformation Matrix} = T_c^{\mathrm{T}}\, T_h\, \Gamma\, \Gamma_\theta\, \overline{\Gamma}^{\mathrm{T}}$$

Rotation θ about common hinge line

Convected System

Hinge Body System

Embedded Hinge Line On Element End

Embedded Hinge Line On Hinge Body

For small deformations:

$$\text{Deformation Matrix} = \begin{bmatrix} 1 & -\phi_z & \phi_y \\ \phi_z & 1 & -\phi_x \\ -\phi_y & \phi_x & 1 \end{bmatrix}$$

ELEMENT DEFORMATIONS

Element deformations are measured from the convected axes. The convected x axis joins the two element end points, so it is fully determined by the translations of the element end points. It is assumed that the finite element grid is sufficiently refined so that element deformations are small, however, the overall member deformations may be large. In fact, the convected analysis was first utilized to treat large deformation rather than large rigid body motion problems. (See for example references 3-7).

Under the small element deformation assumption, the element and convected axes are related by,

$$T_e = T_c D$$

$$D = \begin{vmatrix} 1 & -\phi_z & \phi_y \\ \phi_z & 1 & -\phi_x \\ -\phi_y & \phi_x & 1 \end{vmatrix}$$

Since T_e is related to T_h, the deformation matrix D is given by,

$$D = T_c^T T_h \Gamma \, \Gamma_\theta \Gamma^T$$

and the flexural deformation angles are given by,

$$\phi_y = (1,0,0) T_c^T T_h \Gamma \, \Gamma_\theta \Gamma^T (0,0,1)^T \; ; \; \phi_z = -\,(1,0,0) T_c^T T_h \Gamma \, \Gamma_\theta \Gamma^T (0,1,0)^T$$

The twist over the member or change in roll rotation is given by,

$$\Delta\phi_x = (0,0,1) [\Gamma \, \Gamma_\theta^T \Gamma^T T_h^T]_1 \; [T_h \Gamma \, \Gamma_\theta \Gamma^T]_2 (0,1,0)^T$$

where subscripts 1 and 2 refer to the two ends of the element.

It is important to note that extraction of element deformations only requires defining the convected axis joining the two element ends and not any axes orthogonal to it.

Equations of Motion and Their Numerical Integration

At n^{th} time step,

$$M^n a^n + f^n = F^n$$

Newmark-Beta Integrator at k^{th} iteration:

$$a_k^n = a_{k-1}^n + \left[M_{k-1}^n + \frac{h}{2}G_{k-1}^n + \beta h^2 K_{k-1}^n\right]^{-1} R_k^n$$:Update Accelerations

$$R_k^n = \text{iterative residual} = F^n - f_{k-1}^n - M_{k-1}^n a_{k-1}^n$$

$$V_k^n = V^{n-1} + \left(\frac{h}{2}\right)\left(a^{n-1} + a_k^n\right)$$:Update Velocities

Split into translational and rotational d.o.f.

Translational displacements are

$$d_k^n = d^{n-1} + hv^{n-1} + \left(\tfrac{1}{2} - \beta\right)h^2 a^{n-1} + h^2 a_k^n$$:Update Translational d.o.f.

Rotational motions are given by transformation matrix:

$$T_k^n = \left[1 + h\overline{\omega}_k^n + \tfrac{1}{2}h\left(\overline{\omega}_k^n\right)^2\right]T^{n-1}$$:Update hinge body transformation

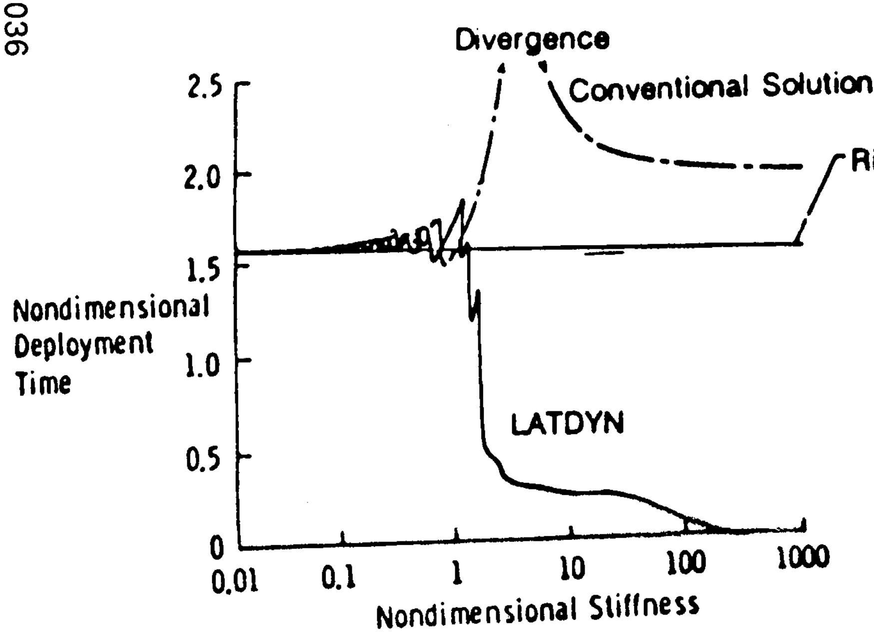
EQUATIONS OF MOTION AND THEIR NUMERICAL INTEGRATION

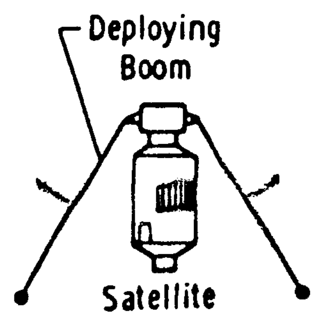
In the figure, h is the time step; M, K and G are the mass stiffness and gyroscopic matrices respectively; a, v and d are acceleration, velocity and translational displacement respectively; f is the nonlinear internal force vector whose linearized terms come from K and G; F is the external force vector; R is the iterative residual; ω is the antisymmetric matrix of angular velocity components and T is the hinge body transformation matrix.

Use of Newmark-Beta yields unconditional numerical stability for linear problems and thus can be expected to permit large time steps. The recursion formulas are second order accurate and it can be shown that the predicted transformation matrix retains orthogonality to third order.

COMPARISON OF SOLUTIONS FOR DEPLOYMENT OF FLEXIBLE BOOM

CONVENTIONAL SOLUTION
CAN DIVERGE
-NONLINEAR KINEMATICS
-LINEAR STRUCTURE





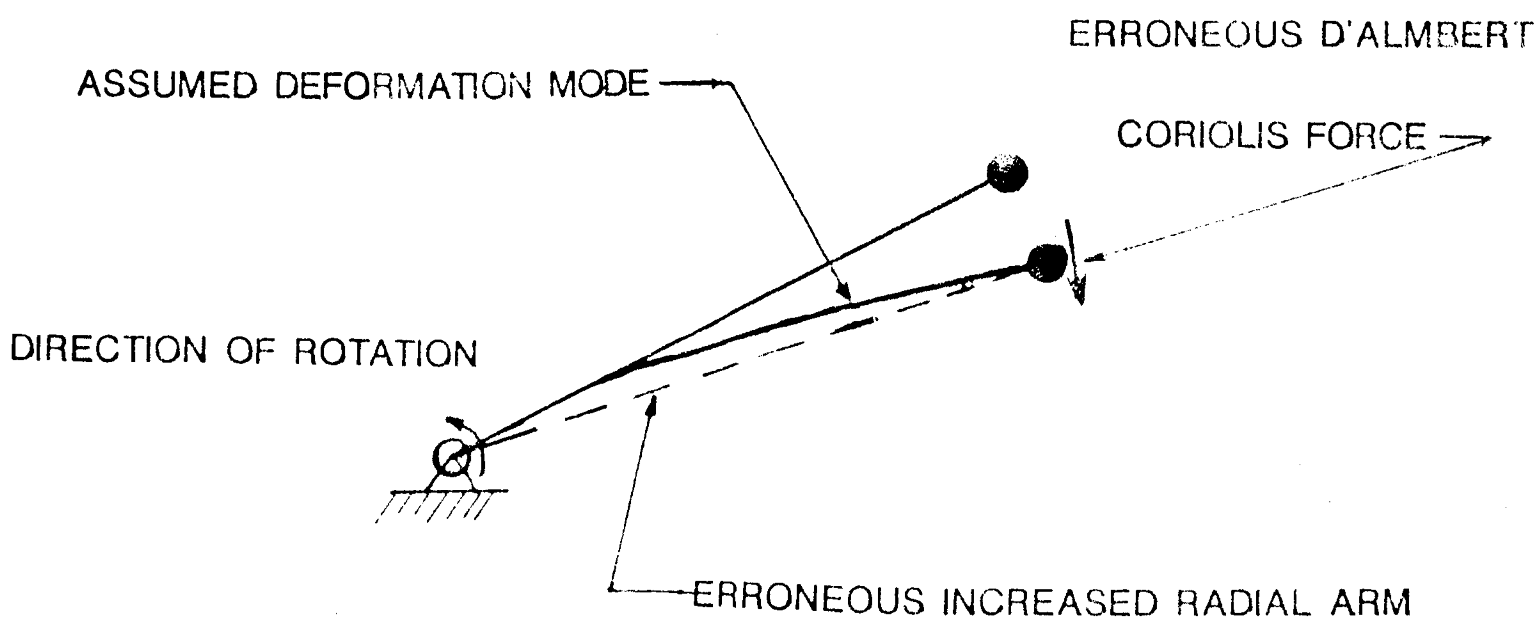
NEED TO USE
NONLINEAR STRUCTURE
WITH
NONLINEAR KINEMATICS

COMPARISON OF SOLUTIONS FOR DEPLOYMENT OF FLEXIBLE BOOM

The common use of a linear structural representation can lead to serious difficulaties when the linear structure is combined with the nonlinear kinematics of large angular motion. For example, the use of mode shapes with nonlinear kinematics can produce erroneous results. This is demonstrated in the accompanying figure which is taken from reference 1 with minor changes.

The curve labeled conventional solution was generated using a linear structural and nonlinear kinematic representation. Deployment time is taken as the time it takes the root to rotate ninety degrees, which is assumed to be the boom's final position. The results indicate divergence and are physically unacceptable as the nondimensional stiffness increases. The increase of this parameter implies either increasing deployment rate or boom softening. As shown in reference 1, such erroneous results occur due to the neglect of nonlinear stuctural terms; that is a linear structural representation with a nonlinear kinematics is unacceptable. On the other hand, a consistent nonlinear approach yields reasonable results.

ERRONEOUS DESTABILIZING CORIOLIS FORCE ON ROTATING BOOM DUE TO COUPLING OF LINEAR STRUCTURAL AND NONLINEAR KINEMATICS MODELING



ERRONEOUS DESTABILIZING CORIOLIS FORCE ON ROTATING BOOM DUE TO COUPLING OF LINEAR STRUCTURAL AND NONLINEAR KINEMATICS MODELING

The divergence demonstrated in the previous figure can be understood physically by considering the sketch of figure 3. Though admittedly considerably simplified, the sketch depicts the erroneous occurrence of a Coriolis force when the flexural deformation is not properly coupled nonlinearly to the radial motion so that axial strain in the member is accurately predicted. The assumed transverse motion in the sketch creates an apparent increase in the radial arm length from the center of rotation. In turn this means an apparent outward radial motion on a rotating boom. Consequently, an erroneous destabilizing Coriolis force arises which acts to increase the deformation, thus causing an even greater destabilizing Coriolis force to appear. If the boom lacks the stiffness to return itself to its straight position, it will become destabilized.

FUTURE WORK

- Three dimensional version now being coded and tested
- Implementation of time integration procedures for parallel processing developed by Brown University
- Assessment of University of Colorado Constraint Stabilization Technique
- Experimentation on a class of fundamental benchmark problems to assess code validity

FUTURE WORK

The three dimensional version of the LATDYN program is now being coded. The program's formulation and sample results will be presented at the 29th Structures, Structural Dynamics and Materials Conference in Williamsburg VA, April 1988. Implementation of the time integration method developed at Brown University is being examined on the Alliant FX-8 and Cray 2 computers and the assessment of the University of Colorado constraint stabilization technique is presently taking place. Lastly, a class of fundamental benchmark cases is to be established which will permit method validation.